

Full length article

Shallow and intermediate depth earthquakes in the Hindu Kush region across the Afghan-Pakistan border

Khaista Rehman^{a,*}, Wajid Ali^a, Asghar Ali^b, Aamir Ali^c, Adnan Barkat^d^a National Centre of Excellence in Geology, University of Peshawar, Khyber Pakhtunkhwa 25120, Pakistan^b Department of Geology, University of Peshawar, Khyber Pakhtunkhwa 25120, Pakistan^c Department of Earth Sciences, Quaid-e-Azam University, Islamabad, Pakistan^d Centre for Earthquake Studies, National Centre for Physics, Islamabad, Pakistan

ARTICLE INFO

Keywords:

Earthquakes

Seismicity

Shallow earthquake

Intermediate earthquakes

Hindu Kush

ABSTRACT

We investigated the spatio-temporal seismicity parameters of shallow (0–70 km) and intermediate (70–300 km) depth earthquakes in the Hindu Kush region, which is characterized by the occurrence of large earthquakes in a small zone of intense activity. By way of comparison, intermediate depth earthquakes dominate the Hindu Kush seismicity. Using a catalogue of 3820 earthquakes, we determined the various earthquake histograms, time-series plots, variations of frequency-magnitude distribution (b-value) and seismicity rate changes (z-value). Both time periods, encompassing pre- and post-1964 subsets of earthquakes, differ significantly in terms of reporting earthquakes, b- and z-value for shallow and intermediate seismicity. The b-values appear to be lower (1.07 and 0.90) for intermediate depth earthquakes than do the b-values produced by shallow earthquakes (1.32 and 1.06) using the pre- and post-1964 data sets. The three low b-value (< 0.9) areas have been identified within the intermediate depth seismicity region of the Hindu Kush. The z-value maps show that the earthquakes with magnitude of 7.0 and above can only be seen in the intermediate depth earthquake maps.

1. Introduction

The arcuate shaped Himalaya-Karakoram-Hindu Kush-Pamir (HKHP) ranges, which collectively comprise the northernmost part of Pakistan and adjacent countries, is the most active seismotectonic terrain (Yin, 2006). These ranges are episodically formed as a result of the Hindu Kush, Karakoram, Kohistan Island Arc and the Indian plate collision with the Eurasian plate following the closure of the Tethys Ocean from the Jurassic to Eocene (Faisal et al., 2014). Collectively, the northernmost part of Pakistan is the eastern continuation of the greater Alpine-Himalayan system, which extends over approximately 7000 km from the Mediterranean Sea in the east to the Sumatra arc of Indonesia in the west (Kearey and Vine, 1990). This immense orogenic system had a profound effect on thrust- and fold-induced topography, tectonic burial, global atmospheric circulation, seismicity, geothermal fields that control diagenetic/metamorphic and anatexis processes, foreland sedimentation, exhumation and structural architecture of the crust that influence the socio-economic life of more than one-fifth of the world's

population. Seismic activity in Pakistan is concentrated at the convergent plate boundaries defined by the Rushan-Pshart suture, Wakhan suture, Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT; Faisal et al., 2014; Fig. 1). Moreover, the concentration of movements along the Main Boundary Thrust, Hazara-Kashmir Syntaxis and Nanga Parbat Syntaxis indicate that the interior parts of the Indian plate are still tectonically active (Fig. 1; Molnar and Tapponnier, 1975; Kearey and Vine, 1990; Treloar et al., 1992; Beck et al., 1995; Kazmi and Jan, 1997; Burg et al., 2005; DiPietro et al., 2008; Faisal et al., 2014; Rehman et al., 2014, 2015). Rehman et al. (2015) divided northern Pakistan into three broad seismotectonic domains, known as Himalaya, Karakoram and Hindu Kush. In general, shallow earthquakes characterize the Himalaya and Karakoram domains, while the Hindu Kush is famous for intense and intermediate depth earthquakes. The 1974 Pattan earthquake, at a depth ranging from 8 to 10 km (Jackson and Yielding, 1983), and the 2005 Kashmir earthquake, at a depth of 26 km (Peiris et al., 2008), are the typical examples of shallow earthquakes in the Kohistan Island Arc and Himalayas, respectively. Conversely, the

* Corresponding author.

E-mail address: rehmannceg@upesh.edu.pk (K. Rehman).

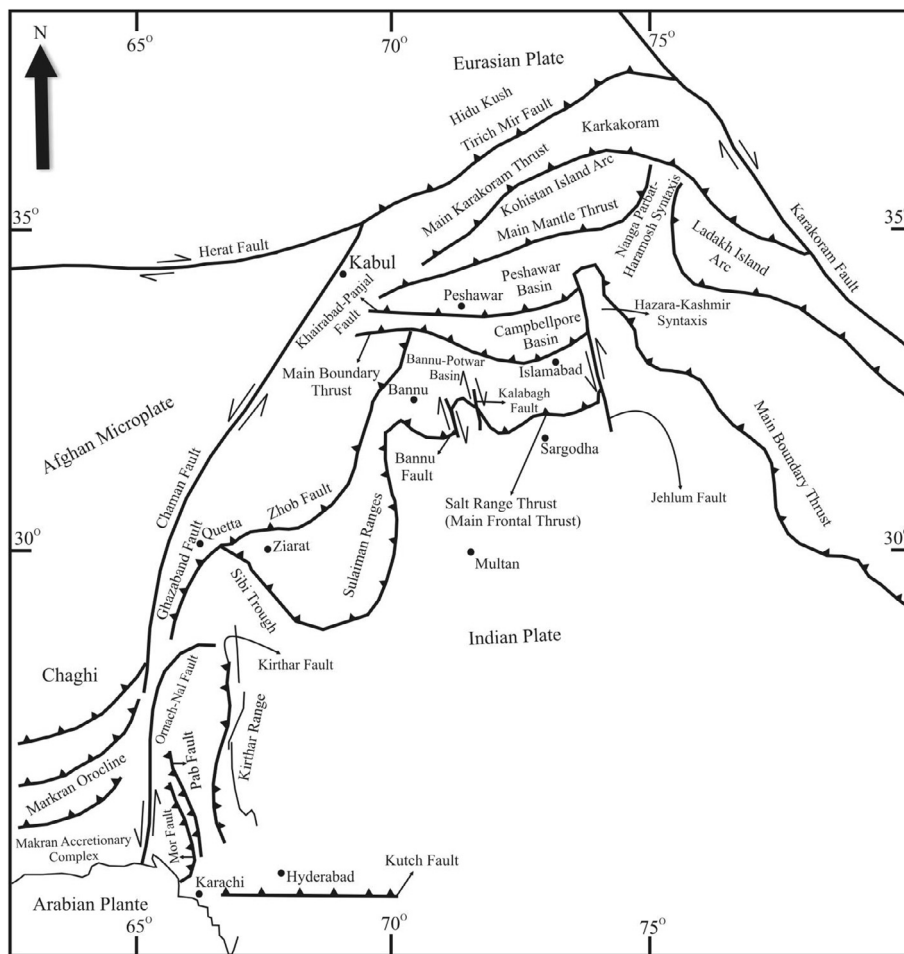


Fig. 1. Map of the present day tectonic grain of Pakistan showing plate boundaries, regional thrusts, strike slip faults and syntaxial structures (after Kazmi and Jan, 1997; Rehman et al., 2015).

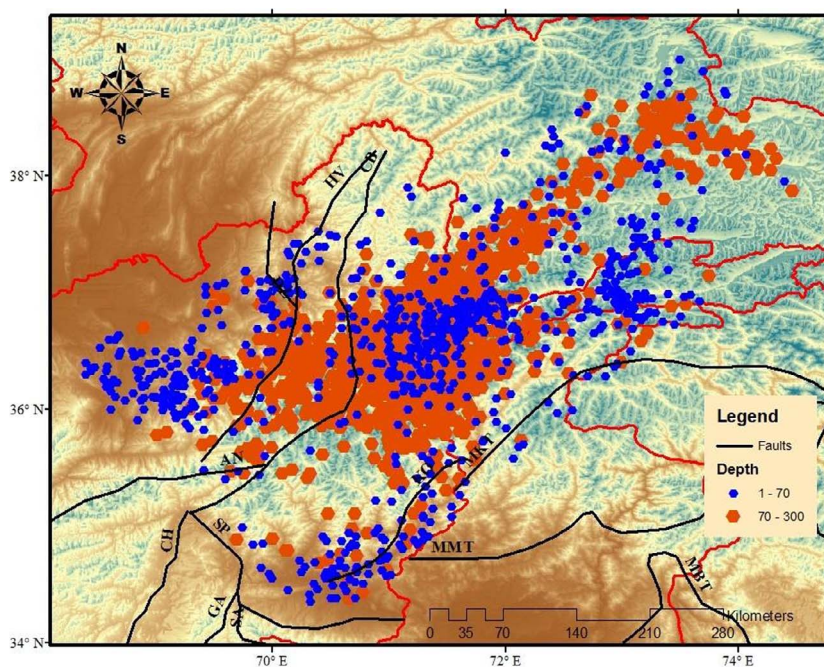


Fig. 2. Earthquake epicenters (blue and orange) between 1900 and 2007 from the earthquake catalog of Rehman et al. (2014). Blacklines denote faults. Abbreviations of fault names: AN, Andarab; CB, Central Badakhsan; CH, Chaman Fault; DZ, Darvaz; GA, Gardez; GF, Ghazaband Fault; HV, Henjvan; MBT, Main Boundary Thrust; MKT, Main Karakoram Fault; MMT, Main Mantle; SA, Sarobi; SP, Spinghar (modified after Wheeler et al., 2005; NESPAK, 2006).

Table 1
Basic statistics of implemented earthquake catalogues.

Number	Catalogue type	Year	Reported earthquakes	Depth (km)
1	ISC	1925–2005	2178	1–292
2	EHB	1964–1995	1141	1–300
3	NEIC	1994–2007	229	7–282
4	GSHAP	1902–1983	216	1–300
5	SSR	1962–1989	42	1–240
6	ABE	1908–1949	14	40–240

Hindu Kush has mostly experienced intermediate earthquakes. Examples of intermediate earthquakes in the Hindu Kush include the 20 February 1998 earthquake ($M_w = 6.4$, depth = 236 km), the 3 March 2002 earthquake ($M_w = 7.4$, depth = 256 km) and the 26 October 2015 earthquake ($M_w = 7.5$, depth = 210 km), which caused damages in Afghanistan and Pakistan (USGS, 2002, 2015; Rehman et al., 2015). The predominant damages reported by those earthquakes were casualties. The 1998 and 2002 earthquakes killed 1 and 113 people, respectively, while the October 2015 earthquake claimed 280 lives and injured 1770 individuals in Pakistan (USGS, 2015). The Malakand region of the Khyber-Pakhtunkhwa, located in Pakistan, was affected the most in the 2015 earthquake. There were a total of 115 deaths and 538 injuries reported in Afghanistan in the 2015 earthquake.

In the Hindu Kush region, the Moho has been reported at depth of approximately 70 km and separates the upper crust, which has less seismicity, from the relatively high mantle seismic zone (Roecker, 1981; Ram and Yadav, 1982; Zarifi and Havskov, 2003; Wheeler et al., 2005). According to Zarifi and Havskov (2003), there is no general and unique interpretation for the possible origin of the intermediate earthquakes in the Hindu Kush, which could be associated with a subduction zone. The concentration of earthquakes in the Hindu Kush crustal and mantle zones warrants two separate investigations (Wheeler et al., 2005). This study is aimed at understanding the Hindu Kush seismicity by comparing the shallow (0–70 km) and intermediate depth (70–300 km) earthquakes using various earthquake histograms, time-series plots, b-values, depth-dependent b-values, low and high b-value zones and z-values.

2. Seismotectonics of the Hindu Kush

The present work uses shallow (0–70 km) and intermediate (70–300 km) depth earthquakes which occurred in the area bounded by 34.35–39°N and 68.4–74.47°E (Fig. 2). The magnitude interval considered was 4.08–7.7 during the period of 1900–2007 (Rehman et al., 2014). Wheeler et al. (2005) discussed the relationship of the faults to the major tectonic zones of the Hindu Kush. The location of faults is depicted in Fig. 2 as black lines. The Darvaz fault is seismically active, lying in Afghanistan and Tajikistan. Trifonov (1978) suggested that the Darvaz fault is a region of high seismic slip toward the Afghanistan side,

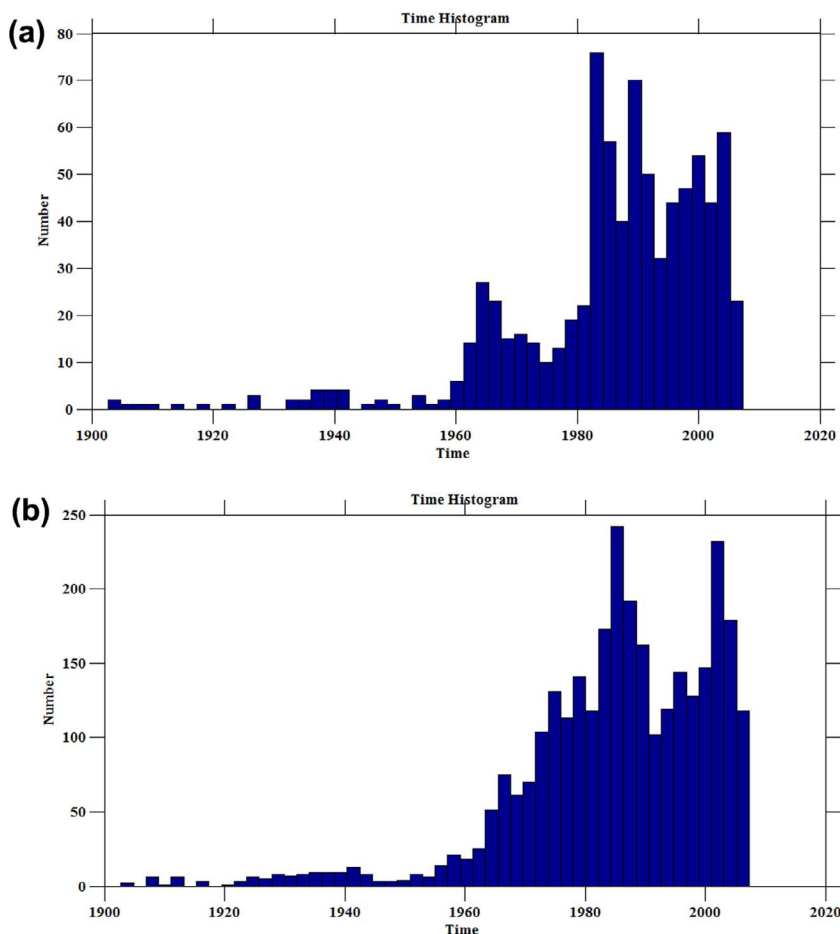


Fig. 3. Time histograms of (a) shallow earthquakes (zone A; 0–70 km) and (b) intermediate earthquakes (zone B; 70–250 km).

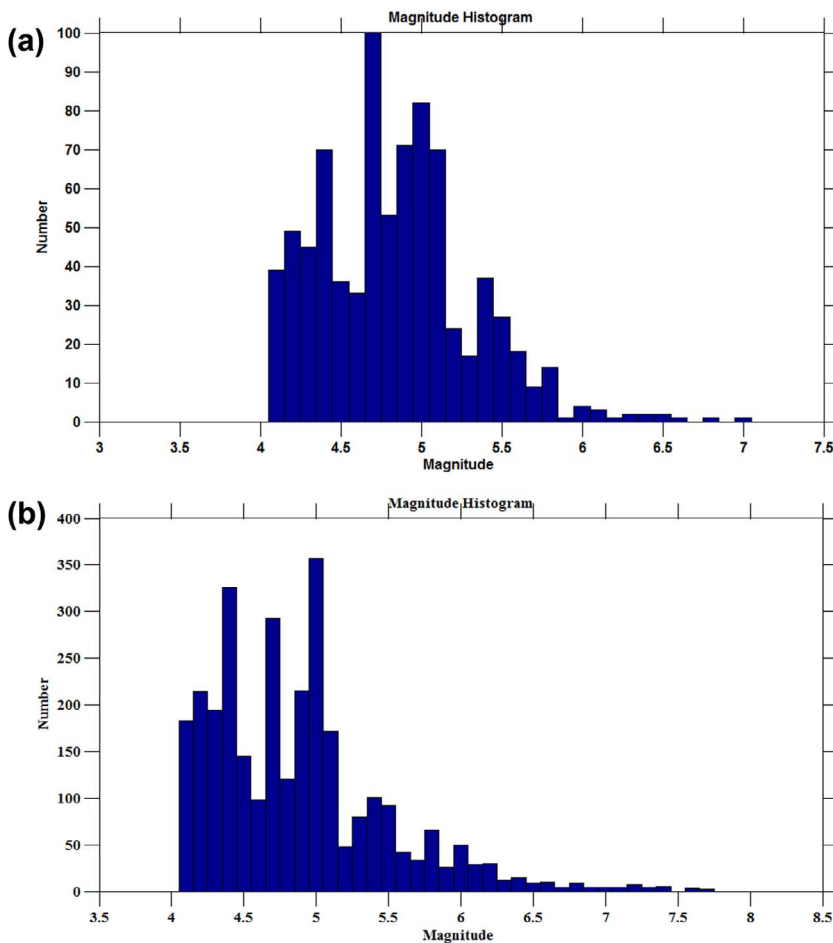


Fig. 4. Histograms of the magnitudes of earthquakes with (a) zone A and (b) zone B.

and earthquakes concentrate along this part of the fault. The other active faults are the Central Badakhshan fault and the Konar fault. The central part of the Central Badakhshan fault contains intense seismic activity extending to depths up to 240 km. Earthquakes of magnitude 7.0 and greater are primarily concentrated in this part of the fault (Table 2). Fig. 2 shows that intermediate depth earthquakes have S-shaped seismicity, while shallow depth earthquakes are primarily concentrated in the North Afghan Platform (69°N, 36.4°E), the junction of the Konar fault and MMT, Pamir (73°N, 37°E) and in the region near the Central Badakhshan fault.

3. Methods

Two important seismological parameters used in frequency-magnitude relation are the b-value and magnitude (M) of an earthquake. The b and M of the Gutenberg and Richter (1944)-GR relationship is represented by

$$\log N = a - bM \quad (1)$$

A number of b-values (the slope of the GR relation) studies have been done in previous years (e.g., Mogie, 1962; Wyss, 1973; Seeber et al., 1980; Urbancic et al., 1992; Schorlemmer et al., 2005; Khan and Chakraborty, 2007; Sarkarinejad et al., 2013; El-Isa and Eaton, 2014; Maden and Ozturk, 2015; Singh and Singh, 2015). These findings suggest that the value of b may be related to tectonic, material

heterogeneity and stress level. The higher b-value is due to weak and heterogeneous rocks, lower stress and numerous smaller earthquakes, while the smaller values of b indicate an increase in stress and homogeneity.

The robust method of maximum curvature is used to evaluate the temporal variation in the magnitude of completeness, and its uncertainty from the GR relation (Wiemer and Wyss, 2000; Woessner and Wiemer, 2005; Fig. 9). The method of maximum curvature suggests that the completeness magnitude (M_c) of Mw 5.0 seems reasonable for the region of Hindu Kush. Zarifi and Havskov (2003) used a threshold value of 4.8 Mb (body wave magnitude) for the Hindu Kush. This value of Mb is approximately equal to Mw 5.0 using the empirical global magnitude conversion relations of Scordilis (2006). The earthquake catalogue for the Hindu Kush used is drawn from the magnitude homogenized earthquake catalogue of Rehman et al. (2014). The homogeneous earthquake catalogue is the primary input in the study of seismicity variation (Habermann, 1987; Burton, 1990; Katsumata, 2011). Rehman et al. (2014) purified various existing earthquake catalogues (e.g., International Seismological Centre (ISC), EHB (Engdahl-Hilst-Buland; Engdahl et al., 1998), U.S. Geological Survey's National Earthquake Information Centre (NEIC), Global Seismic Hazard Assessment Programme (GSHAP; Zhang et al., 1999), ABE - Abe and Kanamori (1979) and SSR - Kondorskaya and Shebalin (1982)), and used appropriate magnitude conversion relations (Scordilis, 2006) to obtain a homogenized earthquake catalogue for Pakistan. All magnitude values

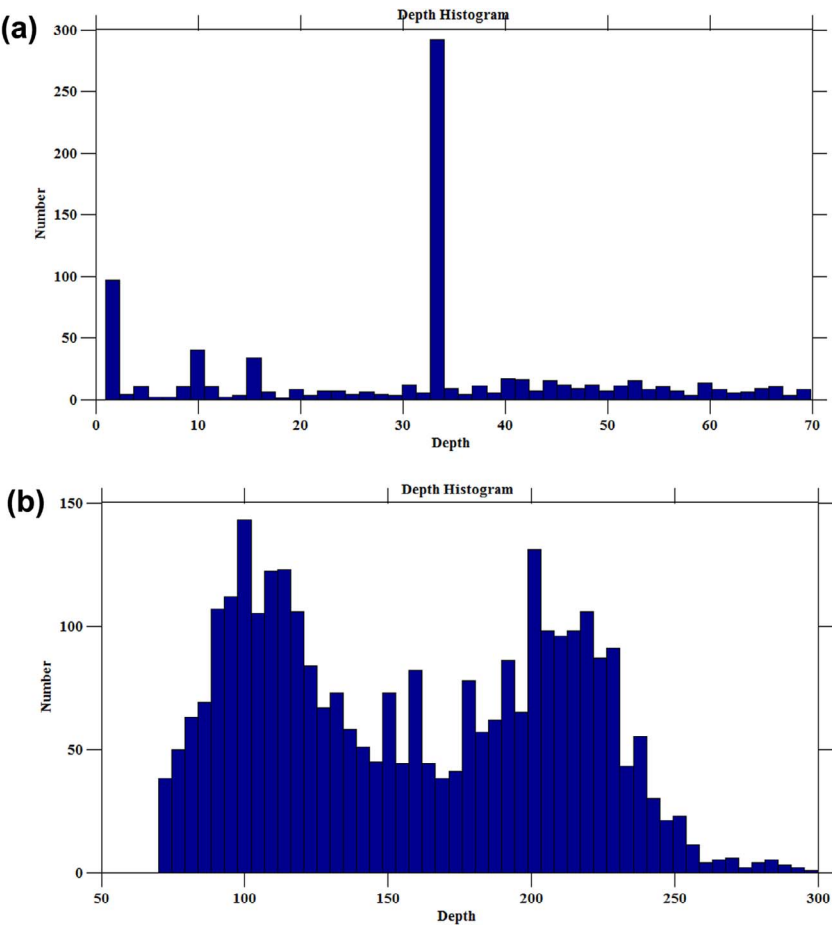


Fig. 5. Histograms in (a) and (b) show depth difference with respect to the number of events for A and B seismicity, respectively.

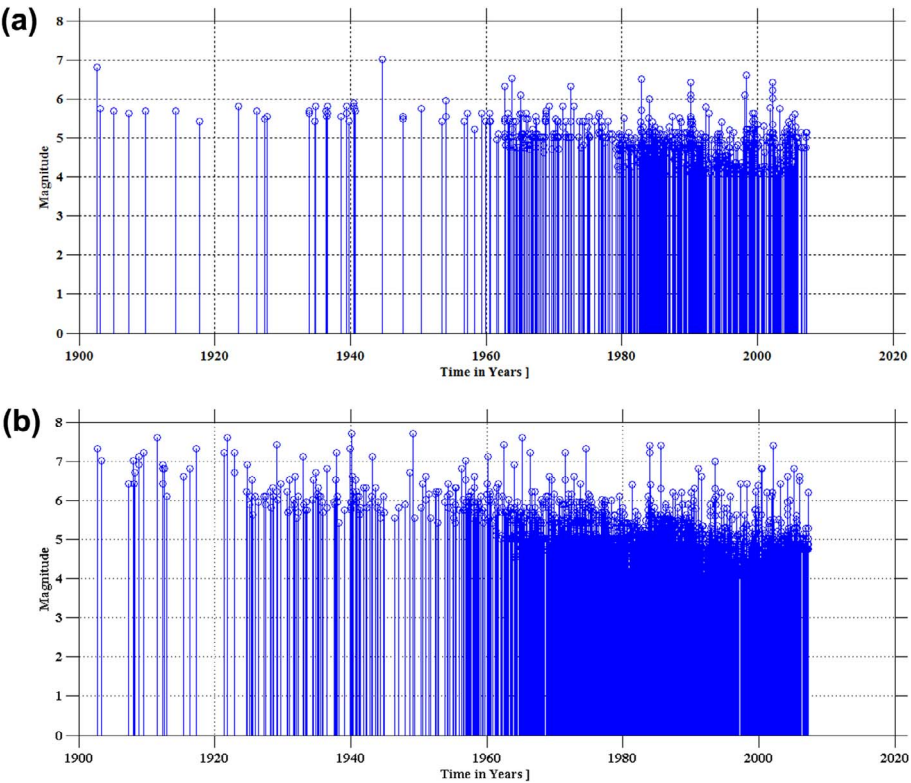


Fig. 6. Plots of earthquake magnitude versus time for (a) zone A and (b) zone B earthquakes.

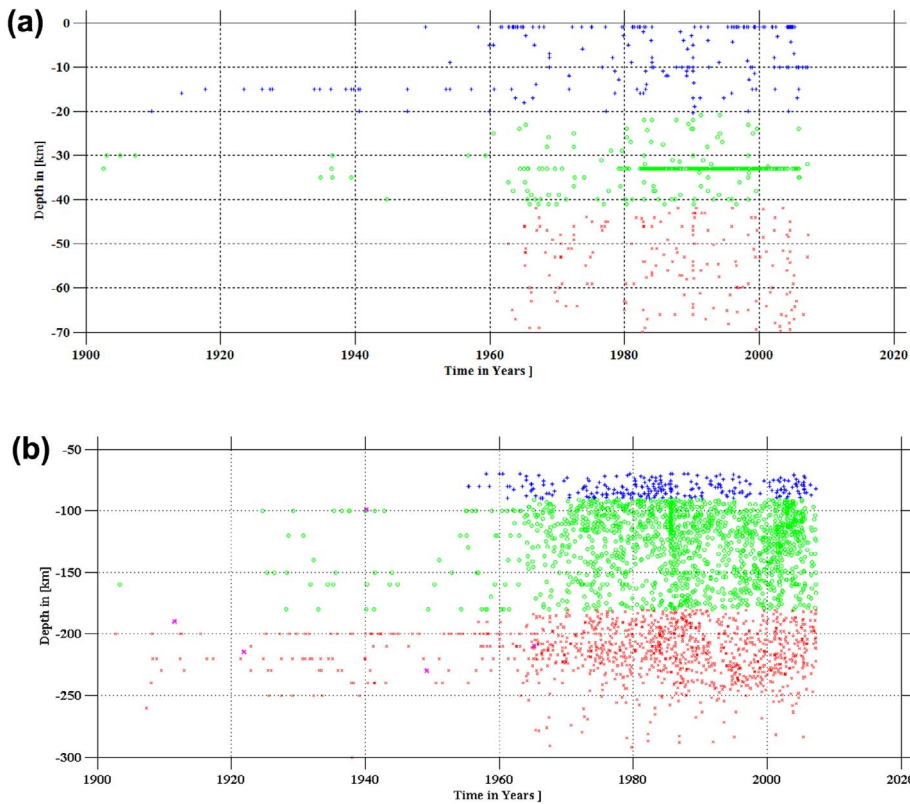


Fig. 7. Depth variation of the seismicity for (a) zone A and (b) zone B.

discussed in the current study are expressed in moment magnitude (Mw) scale using a homogenized earthquake catalogue of Pakistan after Rehman et al. (2014). The homogenized catalogue for Pakistan has been produced using the abovementioned catalogues data taken from the British Geological Survey (BGS; [The BGS World Seismicity Database, 2004](#)) and National Engineering Services Pakistan (Pvt) Limited (NESPAC; [NESPAC, 2006](#)). Table 1 summarizes the basic statistics of the implemented catalogues for the Hindu Kush.

When analyzing the spatial-temporal behavior of earthquakes, it is most important to consider a homogeneous earthquake catalogue (Burton, 1990; Burton et al., 2004; Bayliss and Burton, 2007; Yadav et al., 2011; Das et al., 2012; Rehman et al., 2014). However, there is often a need to describe the parameters of the earthquake catalogue in error terms. In this regard, Maggi et al. (2000), Waldhauser and Schaff (2007) and Camanni et al. (2016) developed useful methods to enable errors in regional and global catalogues. Maggi et al. (2000) used the method of synthetic seismogram to study the depth distribution of earthquakes. Waldhauser and Schaff (2007) developed a double-difference method to reveal improvements in global event locations. Camanni et al. (2016) used a statistical method of collapsing for standard errors in hypocenter locations. The implemented earthquake catalogue for the Hindu Kush is dominated by major available sources of ISC and EHB data (Table 1). ISC routinely update the global earthquake parameters data and provide the most comprehensive available earthquake catalogue for seismic hazard studies (Burton et al., 2004; Waldhauser and Schaff, 2007; Yadav et al., 2011). ISC reanalyze and expand the existing NEIC catalogues using additional seismic phase data. The updated catalogue of EHB (Engdahl et al., 1998; ak135 model) is generally considered to be a modern and accurate catalogue

that is available for global seismic studies due to the significantly improved hypocenter determination (Bondar et al., 2004; Pesicek et al., 2010). Elements that serve to control the EHB model are subsequently identified. For example, relocation of well-constrained hypocenter locations, phase arrivals of P, S and PKP, teleseismic depth phases pP, pwP and sP, Ellipticity, station corrections and weighting pattern using phase variance as a function of distance. The approximate depth error in the EHB catalogue is 10 km, which is slightly lower than the ISC catalogue (Pesicek et al., 2010).

The present analysis uses the method of maximum-likelihood as the most appropriate and more reliable approach for estimation of the b-value than the least square technique (Aki, 1965; Utsu, 1965; Bender, 1983; Woessner and Wiemer, 2005; Singh and Singh, 2015). b-value analysis using the method of maximum likelihood is given by the following relation:

$$b = \log_{10} e (1/\bar{M} - M_{\min}) \quad (2)$$

where $\bar{M}$ and $M_{\min}$ are the average magnitude and threshold magnitude, respectively.

Z-statistics (Wiemer and Wyss, 1994; Kawamura et al., 2014) for comparing the spatio-temporal seismicity rate changes of the areas is given below:

$$z(t) = \frac{(\lambda_1 - \lambda_2)}{\sqrt{\left(\frac{\sigma_1}{n_1} + \frac{\sigma_2}{n_2}\right)}} \quad (3)$$

where λ_i , σ_i and n_i are the mean seismicity rates, the variances and the number of earthquakes in two different time periods, respectively.

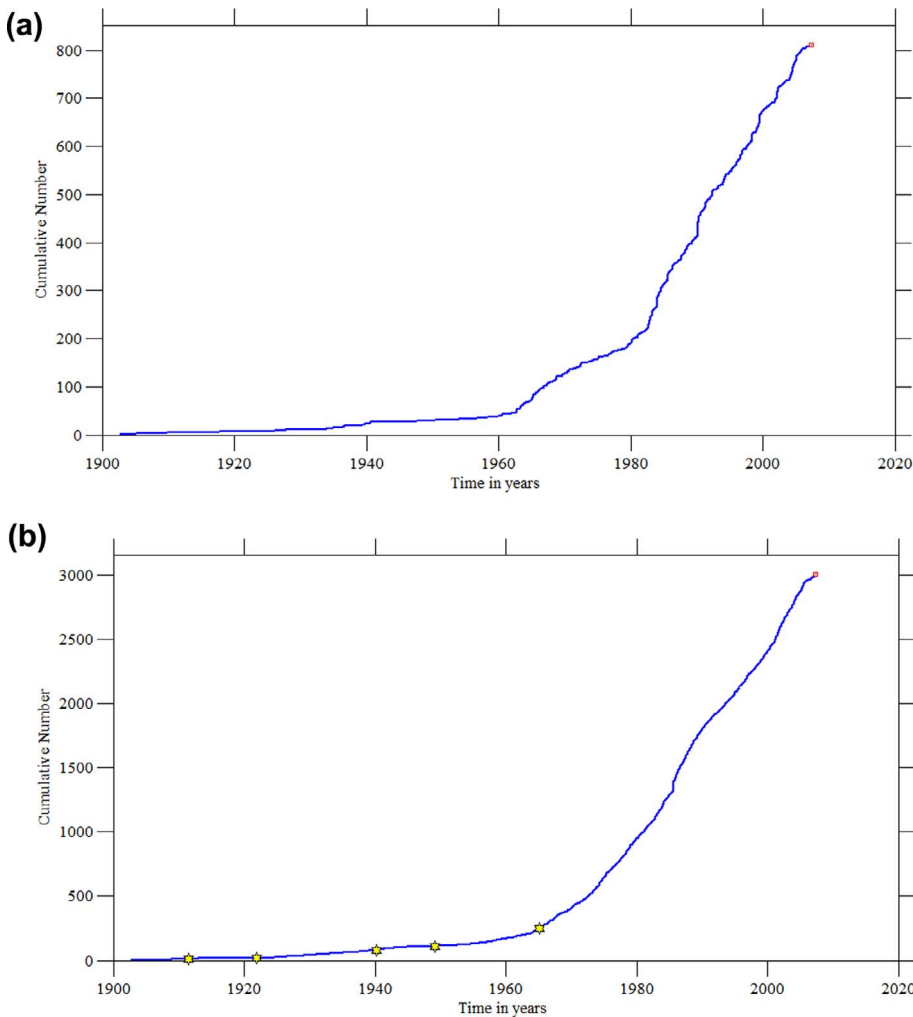


Fig. 8. Cumulative seismicity curves for (a) zone A and (b) zone B.

4. Results and discussion

In this study, two zones, A (shallow earthquakes) and B (intermediate earthquakes) are compared and analyzed using (1) histograms of earthquakes (frequency of earthquakes vs time, magnitude and depth), (2) time series plots, (3) the b-values (depth-dependent-b and the resulting high b-values zones), and (4) z values, which are shown in Figs. 3–5, Figs. 6 and 7, Figs. 8–10 and Figs. 11 and 12, respectively.

Figs. 3–5 show the relevant time, magnitude and depth histograms of the seismicity data. From the time histograms of shallow (Fig. 3a; 0–70 km) and intermediate (Fig. 3b; 70–250 km) depth earthquakes in the Hindu Kush, it is apparent that seismicity data are divided into two main types of time periods (pre- and post-1960). This is simply due to the large number of earthquake events that were reported in the post-1960 period. Both histograms show a dramatic rise in the number of earthquakes reported during the post-1960 period. This increase is due to the international seismograph networks of WWSSN with an improved and developed earthquake monitoring system during the 1960s (Burton et al., 2004). Fig. 3a and b compares the pre- and post-1960 distribution of shallow and intermediate depth earthquakes in the Hindu Kush. It helps to explain that the increase in the zone B seismicity is much higher than the zone A. Zone B shows a higher frequency end (approximately 240) than that of A (approximately 60). Similarly, the

frequency of zone B events is higher (between 0 and 25) than the zone A (between 0 and 8) pre-1960. Comparison of zone A and B events is further evident from the post-1960 data. Confirmation for this finding is provided by the significant increases in the reported earthquakes (more than 200) around two prominent peaks of 1996 and 2001 (Fig. 3b) compared to the 1983 and 1988 peaks in Fig. 3a (70 or greater). Magnitude histograms of zones A and B are shown in Fig. 4a and b, respectively. Both histograms divide the earthquake data into two prominent magnitude ranges: (a) 4.08–5.1 in Fig. 4a, b and (b) 5.2–7.0 in Fig. 4a and 5.2–7.7 in Fig. 4b. On the far right of the histograms, we see low bars until the magnitude 7.0 in zone A, while zone B seismicity displays earthquakes beyond magnitude 7.5. Only one maximum peak, at magnitude 4.7, is identified in zone A, where earthquake frequency has reached to 100. Conversely zone B has three prominent peaks at magnitudes 4.4, 4.7 and 5.0, where earthquakes are more than 270. The frequency of earthquakes decreases beyond magnitudes 5.1 and 5.4 in zone A and zone B, respectively. Zones A and B depth histograms are presented in Fig. 5a and b, respectively. In addition to one prominent peak that has high frequency (≥ 250 earthquakes) at a depth of 33 km (Fig. 5a), which is the ISC default depth for unknown earthquakes depth (Bolton et al., 2006), there are trends of lower frequency earthquakes in a wider range of depth. Three other peaks of earthquake activity are also observed at 1, 10 and 15 km, where a frequency of more than 30

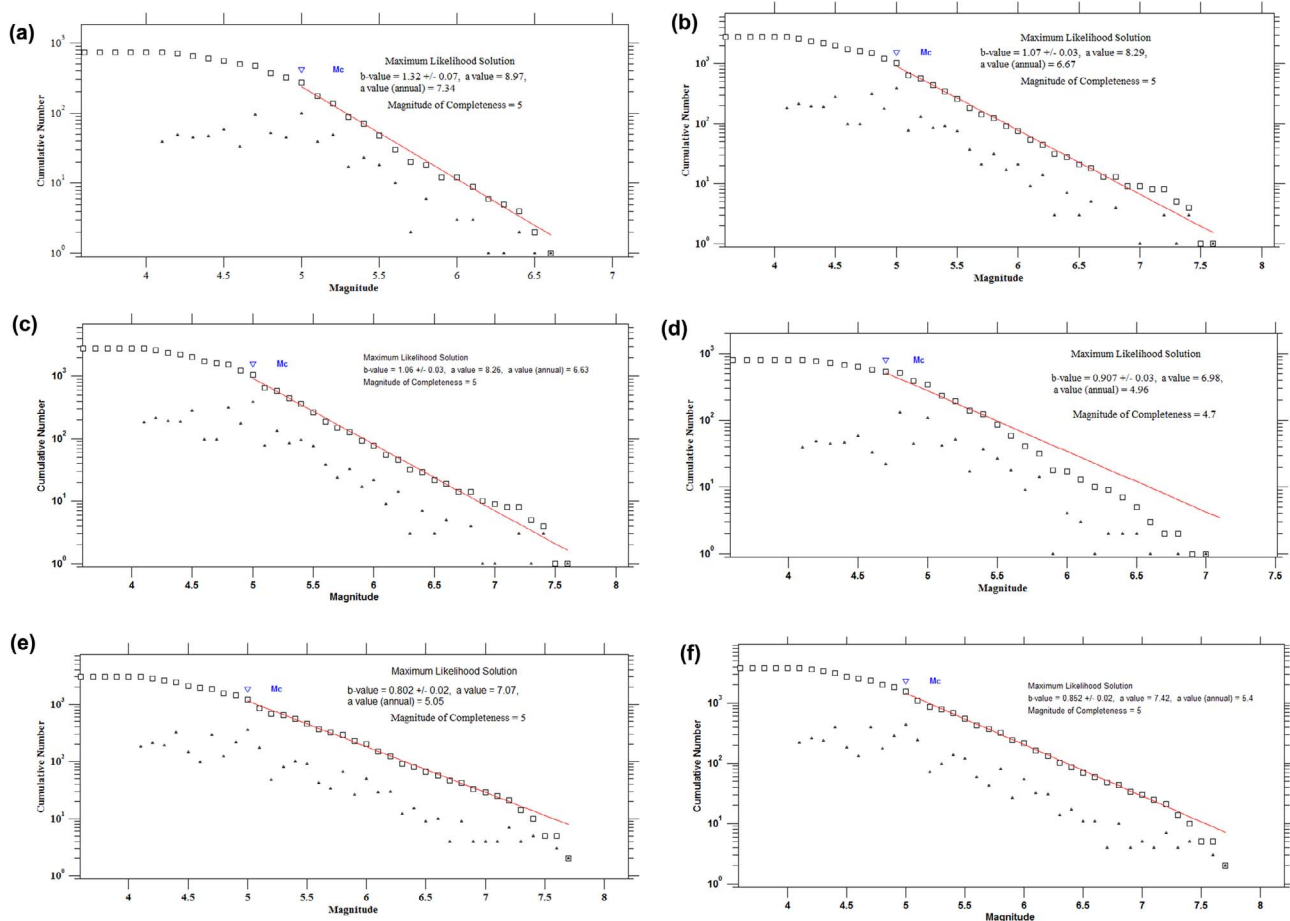


Fig. 9. Cumulative Frequency – Magnitude Distribution of (a) zone A using 1964–2007, (b) zone B 1964–2007, (c) whole of the Hindu Kush using 1964–2007, (d) zone A using 1900–2007, (e) zone B using 1900–2007, (f) whole of the Hindu Kush using 1900–2007.

seems to occur. All other depth bars display the frequency of earthquakes below 20. Frequency of earthquakes increases in the zone B histograms, which show considerable variation in the geographical area of the Hindu Kush (Fig. 5b). Furthermore, it is observed in Fig. 5b that the two depth bar ranges of 88–120 km and 200–220 km have a higher frequency than the remaining bars.

The magnitude distribution in zones A and B of earthquakes as a function of time is shown in Fig. 6a and b. Both figures show that the earthquakes magnitude reported in the Hindu Kush region are primarily after 1963. Most of the earthquake magnitudes were reported in the time span of 1964–2007. Reported magnitude events greater than 6.5 are likely complete since 1900. Similarly, earthquakes as a function of depth increases during the same time period of post-1963, and the time-depth plots of zones A and B seismicity data are displayed in Fig. 7a and b, respectively. Furthermore, similarities and dis-similarities can be seen during pre- and post-1963 in both plots.

Fig. 8a and b shows the cumulative number of earthquakes vs time in zones A and B earthquakes in the Hindu Kush, respectively. Significant changes are clearly observed in the cumulative number of earthquakes as a function of time after 1963. Approximately 70 and 250 earthquakes are reported at the starting date of 1964 in A and B seismicity curve, respectively. Similarly, the maximum reported earthquakes are approximately 820 and 3020 in zones A and B earthquake

plots, respectively. Time histograms (Fig. 3a and b), time variation of seismicity (Fig. 6a and b) and cumulative seismicity curves (Fig. 8a and b) provide the same and consistent time interval of 1964–2007 for the study of b-value calculation as shown in Fig. 9a and b. The b-value, its standard deviation and a-value of the Gutenberg-Richter relation are calculated using the maximum likelihood method because it is a more robust estimation than least-square (Aki, 1965). The time interval of 1964–2007 is considered for b-values calculation of zones A and B. Fig. 9a and b shows the plots of cumulative number of earthquakes against magnitudes of zones A and B earthquakes in the Hindu Kush, respectively. The b-value is calculated as 1.32 ± 0.07 , and Mc is calculated as 5 for shallow seismicity (Fig. 9a). For intermediate depth earthquakes, shown in Fig. 9b, the b-value is calculated as 1.07 ± 0.03 using the same completeness value of $M_c = 5$ mentioned earlier for Fig. 9a. The b-value calculation suggests that the zone A seismicity (b-value = 1.32) is clearly separated from the zone B earthquakes (b-value = 1.07). The finding indicates that large magnitude earthquakes occurred in the area of high stress of low value (intermediate depth), which correlates well with the current scenario (Figs. 4 and 6). The b-value for whole Hindu Kush is found to be 1.06, which is shown in Fig. 9c. This value is close to zone B, which is due to the greater portion of seismic activity concentrated in the intermediate depth. Calculation of the b-value for zone A, B and the

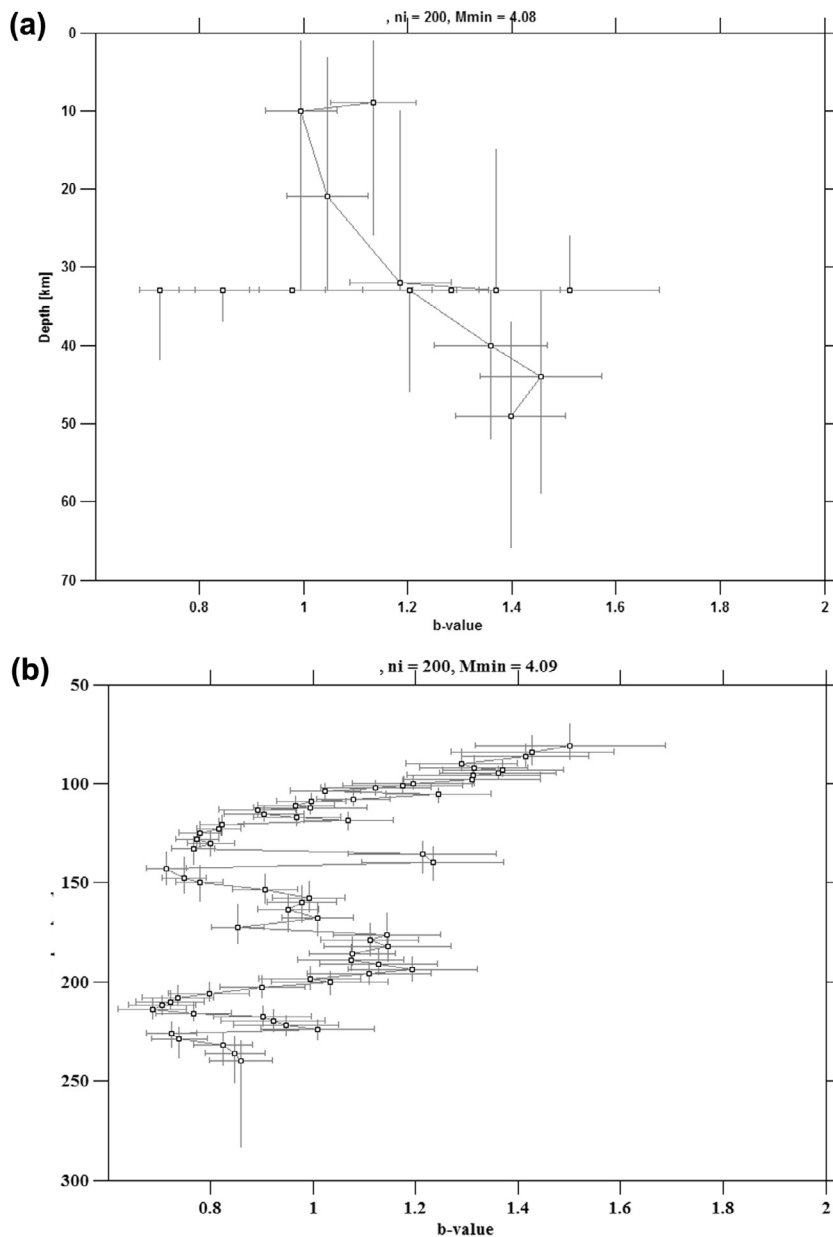


Fig. 10. b-value as a function of depth for (a) zone A and (b) zone B.

whole Hindu Kush is made using the time interval of 1900–2007. B-values for zone A, zone B and the whole Hindu Kush are shown in Fig. 9d, e and f, respectively. Again, the b-value for zone B (0.802) is lower than the b-value for zone A (0.907) and close to the value for the whole Hindu Kush (0.852). The results also reflect the consistent high seismic area of intermediate earthquakes. The b-value range of 0.5–1.5 indicate the tectonic earthquakes environment and the general value is approximately 1.0 (Reasenberg and Jones, 1989). Gutenberg and Richter (1949) estimated the global range of b-value from 0.45 to 1.5 for shallow, intermediate and deep earthquakes. Miyamura (1962) suggested a b-value range of 0.7–1.0 for the region of the Circum-Pacific and Alpine orogenic belts. Zarifi and Havskov (2003) determined the value of b-value in the Hindu Kush is 1.43 using intermediate depth

earthquakes.

Fig. 10 represents the average b-value with standard deviations (horizontal bars) versus the depth of earthquakes in the Hindu Kush. Fig. 10a clearly identifies the ISC default depth of 33 km, where earthquake depth is not available (Bolton et al., 2006). The b-values show a high peak around the depth of 33 km. The b-value range of 1–1.2 is found above the default depth while it increases from 1.2 to 1.5 below 33 km. b-values smaller than 1 are identified in zone B events plot (Fig. 10b). Considerable variation can be seen in the b-value vs depth graph. According to Singh and Singh (2015), b less than 0.9 describes an area of low values for the Hindu Kush and b greater than 0.9 are suggested as high. Following this finding, three zones are associated with the occurrence of intermediate-depth earthquakes having

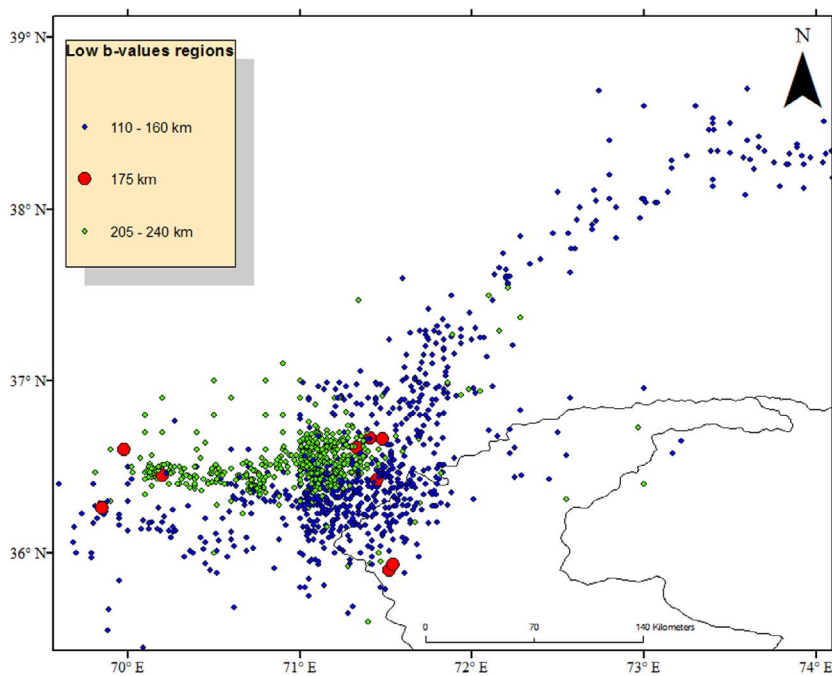


Fig. 11. Low b-value areas of intermediate earthquakes in the Hindu Kush.

b-values lower than 0.9. Zone 1 contains the depth range of 110–160 km. Zone 2 provides low b-values approximately 175 km, and zone 3 considers depth variation ranging from 205 to 240 km. These show considerable variation in the geographical region of the Hindu Kush, as shown in Fig. 11. The clear distinction occurs in the three low b-values regions indicated by blue, red and green colors. More variation occurs in the seismic zone with a depth range of 110–160 km, which extends to the northeast of the Hindu Kush. Clusters of earthquakes occurred at 71–72°E and 36–37°N and contrasts with northeastward and southwestern earthquake events. This zone generated earthquakes with magnitudes up to 7.0. Few earthquakes of low b-values at a depth of 175 km (red color) are shown near the above clustering group of earthquakes. This zone of few earthquakes is characterized by a magnitude of 5.3 or less. Zone 3 earthquakes (green color) are located at 71–71.5°E and 36.25–36.73°N, and the zone become narrow towards southwest. Large earthquake magnitudes of 7.0–7.7 occur in this zone of low b-value. Chatelain et al. (1980) and Zarifi and Havskov (2003) provided the general interpretation of intermediate depth earthquakes of the Hindu Kush and suggested that the earthquakes occur in separated clusters with aseismicity gaps between the clusters.

Fig. 12a and b shows the z-maps for zones A and B earthquakes, respectively. The z-map represents the spatial distribution of the differences of the seismicity changes and it compares the seismicity rates from 1900 to 1965 to those from 1965 to 2007. The blue color (decreased Z-value) and red color (increased Z-value) represent increases and decreases in the seismicity rate changes, respectively. The area shown in Fig. 12a is characterized by low seismicity rate changes except the default depth region approximately 36.5°N and 71.5°E. The Z-value map for zone B earthquakes (Fig. 12b) shows that there is consistent and significant increase in the seismicity rate changes in the three high seismic activity zones as described in Fig. 11. Furthermore, the region of high seismicity rate change has experienced significant earthquakes

in zone 3 with magnitudes of 6.6 (1911, 1921 and 1949) and 7.7 (1940 and 1949) as shown with the yellow stars (Table 2).

5. Conclusions

In this study, two separate investigations were conducted to compare and analyze the distribution of shallow (0–70 km) and intermediate (70–300 km) depth events in the Hindu Kush using various histograms, time-series plots, b and z values. The time variation of seismicity (Fig. 3a and b) shows that more earthquakes are reported during 1964–2007. This shows high seismicity periods after 1980 in case of shallow earthquakes and after 1964 in case of intermediate depth earthquakes. The relation between magnitude and number of earthquakes has been plotted in a magnitude histogram, which represents high percentage of magnitude reported for intermediate depth earthquakes than shallow seismicity. Furthermore, intermediate depth seismicity is characterized by high magnitude earthquakes (greater than 7.5) than shallow earthquakes (only one earthquake with magnitude 7.0). The depth histograms indicate that the frequency of earthquakes is dependent on depth. Approximately 79% of all earthquakes with a depth greater than 70 km are observed, while shallow seismicity region contains 21% of earthquakes. The frequency increases considerably when the depth is below 70 km. From the histograms and time series plots, we conclude that the percentage of reported earthquakes is increased during the post-1964 WWSSN period.

The b-value for shallow and intermediate earthquakes is calculated during 1964–2007. Shallow seismicity region represent relatively higher value of b and shows lower seismicity region. The region of intermediate depth earthquakes has lower b-value of 1.07 and hence shows higher seismicity. This value of 1.07 is close to b-value for the entire Hindu Kush. The same seismicity pattern is determined with a catalogue period of 1900–2007. Seismic b-value within shallow

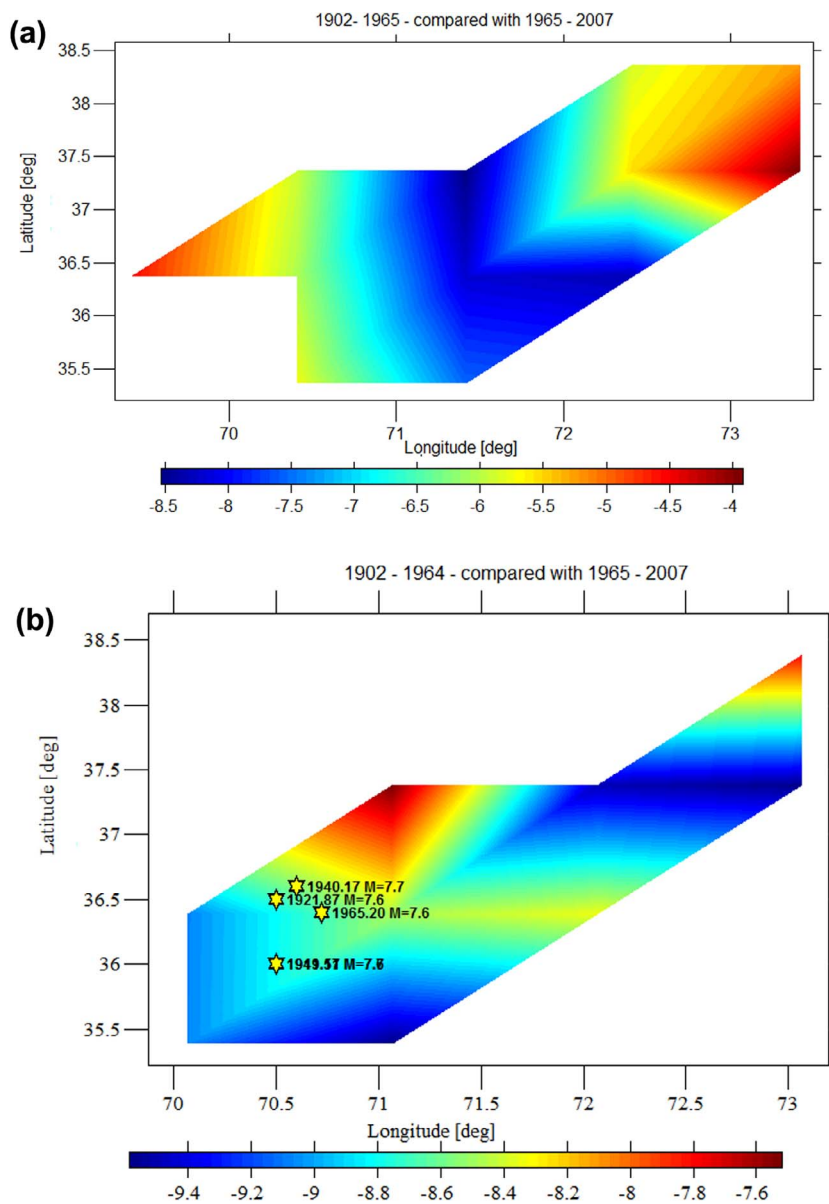


Fig. 12. Seismicity changes for (a) zone A and (b) zone B.

earthquake zones is 0.907. b-values of 0.852 and 0.802 are observed for the intermediate earthquake zone and of the entire Hindu Kush, respectively. Furthermore, the intermediate earthquake region exhibited a variation in b-value and the various zones of b-value less than 0.9 are shown and plotted. Three lower b-values (less than 0.9) areas are suggested: (1) depth range of 110–160 km, (2) depth of 175 km, and (3) depth variation ranged from 205 to 240 km. These results and the earthquake distribution are in agreement with the z-models. There is a consistent increase in the seismicity rate changes in the suggested low b-value areas.

In this study, we show the importance of comparing and separating seismicity of the Hindu Kush into two regions of shallow and intermediate depth using an attractive and advanced seismological tool,

ZMAP. It is shown that the depth range of 70–300 km is more seismically active than the shallow depths. Today, many algorithms are available in the study of seismicity; however, emphasis should be placed on the need to consider the associated errors within the implemented earthquake catalogue.

Acknowledgements

We highly appreciate the facilities provided by the National Centre of Excellence in Geology, University of Peshawar. We also thank two anonymous reviewers for their constructive and helpful comments leading to an improved manuscript.

Table 2
Earthquakes of magnitude 7.0 and greater in the Hindu Kush.

Year	Month	Day	Latitude	Longitude	Depth (km)	Mw
1902	10	6	36.50	70.50	200	7.3
1903	4	19	37.00	71.00	160	7.0
1907	12	25	36.50	70.50	240	7.0
1908	10	24	36.50	70.50	220	7.1
1909	7	7	36.50	70.50	230	7.2
1911	7	4	36.00	70.50	190	7.6
1917	4	21	37.00	70.50	220	7.3
1921	5	20	36.00	70.50	220	7.2
1921	11	15	36.50	70.50	215	7.6
1922	12	6	36.50	70.50	230	7.2
1929	2	1	36.50	70.50	220	7.4
1933	1	9	36.40	69.60	180	7.1
1937	11	14	36.50	70.50	240	7.2
1939	11	21	36.30	70.60	220	7.3
1940	3	4	36.60	70.60	99	7.7
1943	2	28	36.50	70.50	210	7.1
1944	9	27	39.00	73.50	40	7.0
1949	3	4	36.00	70.50	230	7.7
1956	11	14	36.70	70.80	190	7.0
1960	2	19	36.80	71.00	190	7.1
1962	7	6	36.80	70.10	210	7.4
1965	3	14	36.40	70.72	210	7.6
1966	6	6	36.42	71.14	216	7.2
1971	8	4	36.39	70.74	202	7.2
1974	7	30	36.37	70.74	211	7.3
1983	12	30	36.39	70.71	214	7.4
1985	7	29	36.17	70.87	100	7.4
1993	8	9	36.33	70.88	211	7.0
2002	3	3	36.43	70.44	209	7.4

References

- Abe, K., Kanamori, H., 1979. Temporal variation of the activity of intermediate and deep focus earthquakes. *J. Geophys. Res.* 84, 3589–3595.
- Aki, K., 1965. Maximum likelihood estimate of b in the formula $\log N = a - bM$ and its confidence limits. *University of Tokyo. Bull. Earthq. Res. Inst.* 43, 237–239.
- Bayliss, T.J., Burton, P.W., 2007. A new earthquake catalogue for Bulgaria and the continuous Balkan high hazard region. *Nat. Hazards Earth Syst. Sci.* 7, 345–359.
- Beck, R.A., et al., 1995. Stratigraphic evidence for an early collision between northwest India and Asia. *Nature* 373, 55–58.
- Bender, B., 1983. Maximum likelihood estimation of b -values for magnitude grouped data. *Bull. Seismol. Soc. Am.* 73, 831–851.
- Bolton, M.K., Storchak, D.K., Harris, J., 2006. Updating default depth in the ISC bulletin. *Phys. Earth Planet. Interiors* 158 (1), 27–45.
- Bondar, I., Myers, S.C., Engdahl, E.R., Bergman, E.A., 2004. Epicentre accuracy based on seismic network criteria. *Geophys. J. Int.* 156, 483–496.
- British Geological Survey, 2004. The British Geological Survey World Seismicity Database (WSD) Manual.
- Burg, P.J., Celerier, B., Chaudhry, M.N., Ghazanfar, M., Gnehm, F., Schnellmann, M., 2005. Fault analysis and paleostress evolution in large strain regions: methodological and geological discussion of the southeastern Himalayan Fold-and-thrust belt in Pakistan. *J. Asian Earth Sci.* 24, 445–467.
- Burton, P.W., 1990. Pathways to seismic hazard evaluation: extreme and characteristic earthquakes in areas of low and high seismicity. *Nat. Hazard* 3, 275–291.
- Burton, P.W., Xu, Y., Qin, C., Tselentis, G.A., Sokos, E., 2004. A catalogue of seismicity in Greece and the adjacent areas for the twentieth century. *Tectonophysics* 390, 117–127.
- Camanni, G., Marron, J.A., Brown, D., Ayala, C., Wu, Y.M., Hsieh, H.H., 2016. The deep structure of south-central Taiwan illuminated by seismic tomography and earthquake hypocenter data. *Tectonophysics* 679, 235–245.
- Chatelain, J.L., Roecker, S.W., Hatzfeld, D., Molnar, P., 1980. Microearthquake seismicity and fault plane solutions in Hindu Kush region and their tectonic implications. *J. Geophys. Res.* 85, 1365–1387.
- Das, R., Wason, H.R., Sharma, M.L., 2012. Homogenization of earthquake catalog for northeast India and adjoining region. *Pure Appl. Geophys.* 169, 725–731.
- DiPietro, J.A., Ahmad, I., Hussain, A., 2008. Cenozoic kinematic history of the Kohistan fault in the Pakistan Himalaya. *Geol. Soc. Am. Bull.* 120, 1428–1440.
- El-Isa, Z.H., Eaton, D.W., 2014. Spatiotemporal variations in the b -value of earthquake magnitude–frequency distributions: classification and causes. *Tectonophysics* 615–616, 1–11.
- Engdahl, E.R., Hilst, V.R., Buland, R., 1998. Global teleseismic relocation with improved travel times and procedures for depth determination. *Bull. Seismol. Soc. Am.* 88, 722–743.
- Faisal, S., Larson, K.P., Cottle, J.M., Lamming, J., 2014. Building the Hindu Kush: Monazite Records of Terrane Accretion, Plutonism, and the Evolution of the Himalaya-Karakoram-Tibet Orogen. <http://dx.doi.org/10.1111/ter.12112>.
- Gutenberg, B., Richter, C., 1944. Frequency of earthquakes in California. *Bull. Seismol. Soc. Am.* 34, 185–188.
- Gutenberg, B., Richter, C.F., 1949. Seismicity of the Earth and Associated Phenomena. Princeton University Press.
- Habermann, R.E., 1987. Man-made changes of seismicity rates. *Bull. Seismol. Soc. Am.* 77, 141–159.
- Jackson, J., Yielding, G., 1983. The seismicity of Kohistan, Pakistan: source studies of the Hamran (1972.9.3), Darel (1981.9.12) and Patan (1974.12.28) earthquakes. *Tectonophysics* 91, 15–28.
- Katsumata, K., 2011. A long-term seismic quiescence started 23 years before the 2011 off the Pacific coast of Tohoku Earthquake ($M = 9.0$). *Earth Planets Space* 63, 709–712.
- Kawamura, M., Chien-chih, Chen, C.C., Wu, Y.M., 2014. Seismicity change revealed by ETAS, PI, and Z-value methods: a case study of the 2013 Nantou, Taiwan earthquake. *Tectonophysics* 634 (5), 139–155.
- Kazmi, A.H., Jan, M.Q., 1997. *Geology and Tectonics of Pakistan*. Graphic Publishers.
- Kearey, P., Vine, J.F., 1990. *Global Tectonics*. Blackwell Scientific Publications.
- Khan, P.K., Chakraborty, P.P., 2007. The seismic b -value and its correlation with Bouguer gravity anomaly over the Shillong Plateau area: tectonic implications. *J. Asian Earth Sci.* 29, 136–147.
- Kondorskaya, N.V., Shebalin, N.V., 1982. (Russian edition 1975) *New Catalogue of Strong Earthquakes in the USSR from Ancient Times through 1977* (corrected and updated according to second edition), Report SE-31, World Data Centre-A for Solid Earth Geophysics, Boulder, Colorado, USA. 608 pages.
- Maden, N., Ozturk, S., 2015. Seismic b -values, Bouguer gravity and heat flow data beneath eastern Anatolia, Turkey: tectonic implications. *Sur. Geophys.* 36, 549–570.
- Maggi, A., Jackson, J.A., Priestley, K., Baker, C., 2000. A re-assessment of focal depth distributions in southern Iran, the Tien Shan and northern India: do earthquakes really occur in the continental mantle? *Geophys. J. Int.* 143, 629–661.
- Miyamura, S., 1962. Magnitude frequency relation of earthquakes and its bearing to geotectonics. *Proc. Jpn. Acad.* 38, 27pp.
- Mogile, K., 1962. Magnitude–frequency relationship for elastic shocks accompanying fractures of various materials and some related problems in earthquakes. *Bull. Earthq. Res. Inst.* 41, 831–883.
- Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: efforts of a continental collision. *Science* 189, 419–426.
- NESPAK, 2006. *Seismic Resistant Design of Buildings in Pakistan*. National Engineering Services Pakistan (Pvt) Limited.
- Peiris, N., Rossetto, T., Burton, P., Mahmood, S., 2008. Kashmir Pakistan Earthquake of 8 October 2005, A Field Report by EEFIT, Earthquake Engineering Field Investigation Team, Institution of Structural Engineers, London, 119 pages. < www.eefit.org.uk >. ISBN 978 1 906335 11 3.
- Pesicek, J.D., Thurber, C.H., Zhang, H., DeShon, H.R., Engdahl, E.R., Widiyantoro, S., 2010. Teleseismic double-difference relocation of earthquakes along the Sumatra–Andaman subduction zone using a 3-D model. *J. Geophys. Res.* 115, B10303.
- Ram, A., Yadav, L., 1982. Seismotectonics and analysis of earthquakes from the Hindukush region. *Geophys. J. R. Astr. Soc.* 68, 559–574.
- Reasenber, P.A., Jones, L.M., 1989. Earthquake hazard after a main shock in California. *Science* 243, 1173–1176.
- Rehman, K., Burton, P.W., Weatherill, G.A., 2014. K-means cluster analysis and seismicity partitioning for Pakistan. *J. Seismol.* 18, 401–419.
- Rehman, K., Ali, A., Ahmed, S., Ali, W., Ali, A., Khan, M.Y., 2015. Spatio-temporal variations of b -value in and around north Pakistan. *J. Earth Syst. Sci.* 124 (7), 1445–1456.
- Roecker, S.W., 1981. *Seismicity and Tectonics of the Pamir-Hindu Kush Region of Central Asia* (Ph.D. Thesis). Massachusetts Institute of Technology, Cambridge, 294pp.
- Sarkarinejad, K., Zadeh, R.M., Webster, R., 2013. Two-dimensional spatial analysis of the seismic b -value and the Bouguer gravity anomaly in the southeastern part of the Zagros Fold-and-Thrust Belt, Iran: Tectonic implications. *J. Asian Earth Sci.* 62 (30), 308–316.
- Schorlemmer, D., Wiemer, S., Wyss, M., 2005. Variations in earthquake size distribution across different stress regimes. *Nature* 437, 539–542.
- Scordilis, E.M., 2006. Empirical global relations converting M_s and M_b to moment magnitude. *J. Seismol.* 10, 225–236.
- Seeber, L., Armbruster, J., Farhatullah, S., 1980. Seismic activity at Terbel dam site and surrounding region. *Geol. Bull. Uni. Peshawar* 13, 169–191.
- Singh, C., Singh, S., 2015. Imaging b -value variation beneath the Pamir-Hindu Kush Region. *Bull. Seismol. Soc. Am.* 105 (2A), 808–815.
- Treloar, P.J., Coward, M.P., Chambers, A.F., Izzat, C.N., Jackson, K.C., 1992. Thrust geometries, interferences and rotations in the North West Himalaya. In: McClay, K.R. (Ed.), *Thrust Tectonics*. Chapman and Hall, New York, pp. 325–342.
- Trifonov, V.G., 1978. Late Quaternary tectonic movements of western and central Asia. *Geol. Soc. Am. Bull.* 89, 1059–1072.
- Urbanic, T.I., Trifu, C.I., Long, J.M., Young, R.P., 1992. Space-time correlations of b values with stress release. *Pure Appl. Geophys.* 139, 449–462.
- USGS, 2002. *USGS Preliminary Earthquake Report. Hindu Kush Region, Afghanistan*. < http://neic.usgs.gov/neis/eq_depot/2002/eq_020325/ >.
- USGS, 2015. *USGS Preliminary Earthquake Report. Hindu Kush Region, Afghanistan*. < <https://earthquake.usgs.gov/earthquakes/eventpage/us10003re5#executive> >.
- Utsu, T., 1965. A method for determining the value of b in the formula $\log N = a - bM$ showing the magnitude–frequency relation for earthquakes. *Geophys. Bull. Hokkaido Univ.* 13, 99–103.
- Waldhauser, F., Schaff, B., 2007. Regional and teleseismic double-difference earthquake relocation using waveform cross-correlation and global bulletin data. *J. Geophys. Res.* 112, B12301. <http://dx.doi.org/10.1029/2007JB004938>.
- Wheeler, B.R., Bufer, C.G., Johnson, M.L., Dart, R.L., Norton, G.A., 2005. *Seismotectonic Map of Afghanistan, with Annotated Bibliography*. USGS Open File report 2005–1264.
- Wiemer, S., Wyss, M., 1994. Seismic quiescence before the Landers ($M = 7.5$) and Big Bear (6.5) 1992 earthquakes. *Bull. Seismol. Soc. Am.* 84, 900–916.
- Wiemer, S., Wyss, M., 2000. Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan. *Bull. Seismol. Soc. Am.* 90, 859–869.
- Woessner, J., Wiemer, S., 2005. Assessing the quality of earthquake catalogues: estimating the magnitude of completeness and its uncertainty. *Bull. Seismol. Soc. Am.*

- 95, 684–698.
- Wyss, M., 1973. Towards a physical understanding of earthquake frequency distribution. *Geophys. J. R. Astron. Soc.* 31, 341–359.
- Yadav, R.B.S., Bayrak, Y., Tripathi, J.N., Chopra, S., Singh, A.P., Bayrak, E., 2011. A probabilistic assessment of earthquake hazard parameters in NW Himalaya and the adjoining regions. *Pure Appl. Geophys.* 169 (9), 1619–1639.
- Yin, A., 2006. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth Sci. Rev.* 76, 1–131.
- Zarifi, Z., Havskov, J., 2003. Characteristics of dense nests of deep and intermediate-depth seismicity. *Adv. Geophys.* 46, 237–278.
- Zhang, P., Yang, Z., Gupta, H.K., Bhatia, S.C., Shedlock, K.M., 1999. Global Seismic Hazard Assessment Program (GSHAP) in continental Asia. *Ann. Geofis.* 42 (6), 1167–1189.